



## Vibration response of a rotor supported in one rigid and one poorly lubricated fluid film bearing

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This article presents vibrational data taken from a laboratory rotor rig. Poor lubrication and rubbing at the fluid-film bearing caused the appearance of specific fractional sub-synchronous vibrations in the rotor vibrational response.

### Description of the rotor rig

A 0.8 kg (1.8 lb) massive disk rotor, driven by an electric motor (Figure 1), was supported inboard by a laterally relatively rigid, but pivoting, rolling element bearing. The rotor was supported at the outboard end by a T10 oil-lubricated bearing, made of transparent acrylic. In order to center the journal inside the oil-lubricated bearing, the rotor was additionally supported by a radial spring support. The rig was equipped with a speed controller, Keyphasor® transducer, and two pairs of proximity transducers mounted in an XY (horizontal, vertical) configuration near the disk and at the bearing. The fluid-lubricated bearing was pressurized by oil supplied from four radial ports.

### Rotor lateral response data during startup

The rotor was balanced before the experiments. Some residual unbalance in the system remained, however. Figure 2 shows the full spectrum cascade plot of the journal response (see sidebar on page 9) when the bearing oil supply pressure was 4137 Pa (0.6 psi). The normal pressure is above 6895 Pa (1 psi). In the range of lower rotative speeds, the rotor is stable. The only vibrational component is a 1X (synchronous) response to the rotor residual unbalance. At 1620 rpm, the instability threshold occurs, followed, at higher speeds, by the fluid whirl self-excited vibration [1]. The fluid whirl frequency is 0.47X, and the journal fluid whirl

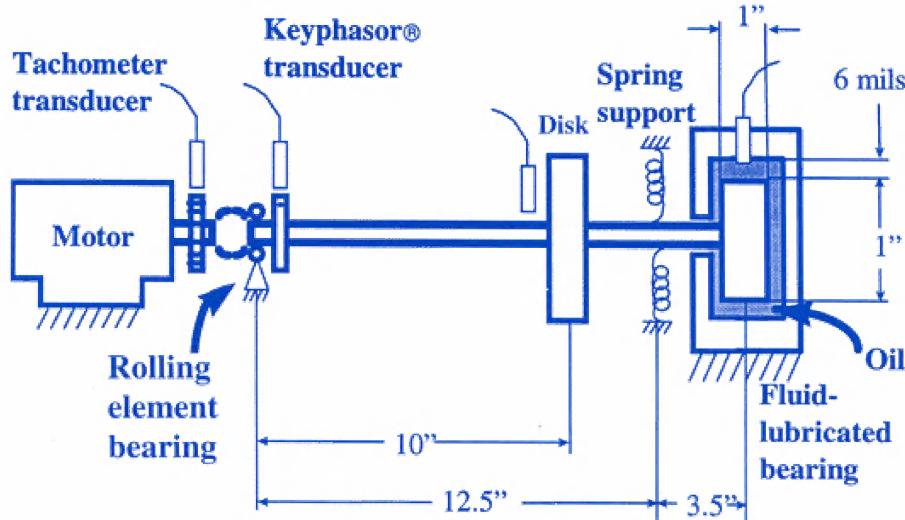
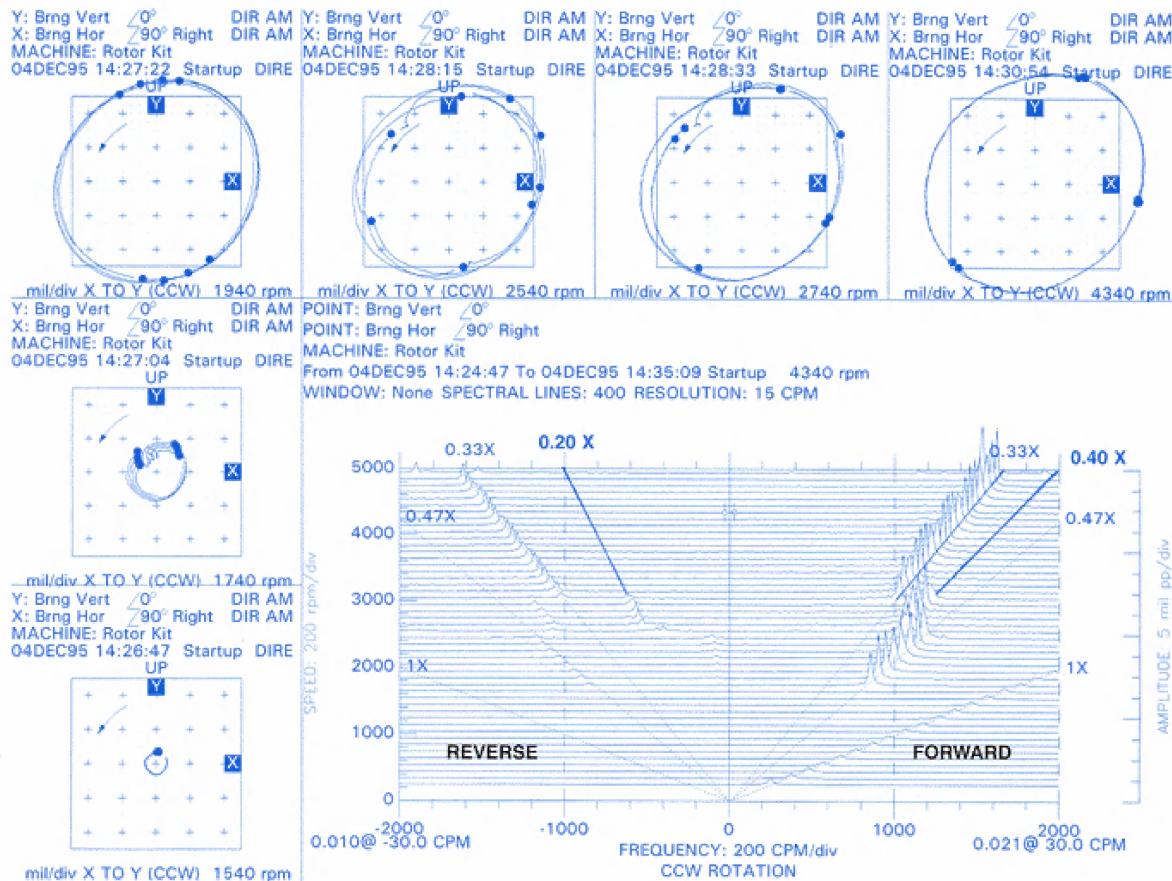


Figure 1  
Rotor rig



**Figure 2**  
Full spectrum cascade plot of the journal response during startup accompanied by orbits at six different rotative speeds. Bearing oil supply pressure was 4137 Pa (0.6 psi).

orbits are forward and slightly elliptical. This classical pattern of the fluid-induced instability shows, also, a presence of a differential sideband component  $1X - 2 (0.47X) = 0.06X$ , which is circular and reverse.

A dramatic change in the journal vibration pattern occurs at 2500 rpm. The fluid whirl  $0.47X$  component disappears, giving way to fractional components: a  $1/5X$  backward component with a circular orbit and its second harmonic,  $2/5X$  forward component with a much larger, slightly elliptical, orbit. The appearance of fractional vibrational components, especially with reverse orbits, is characteristic for cases of rotor-to-stator rubbing [2-6]. Unlike other partial rub cases, the  $2/5X$  forward component here is dominant, so the

direct orbit of the journal is forward (see *Figure 2 full spectrum cascade plot*).

The existence of the  $1/5X$  circular, reverse component indicates, however, that the mechanism of the documented phenomenon is related to friction. Indeed, the oil film pattern observed through the transparent wall of the bearing underwent changes. Instead of regular, uniform oil thickness, some irregular and fast changing oil voids were present. The lubrication pattern became different: From full circumferential ( $360^\circ$ ) lubrication at low speed, it changed to poor (starvation) lubrication with mixed oil and air, allowing for journal-to-bearing physical contacts.

At 3020 rpm, the vibrational pattern  $1/5X$  &  $2/5X$  disappeared, giving way to another fractional, rub-related component, namely  $1/3X$ , with slightly ellipti-

cal forward orbits. This component is visibly more stable and persistent in the range of higher rotative speeds up to 5000 rpm.

Between the clean response patterns described above, there often appeared a chaotic zone of vibration, also typical for the rub-related responses [4,5].

#### Observed phenomena

The full case history of the lateral vibrations of a rotor supported by one rigid and one fluid, poorly lubricated bearing is contained in BRDRC Report [7]. It documents phenomena, which, to the authors' knowledge, have never been documented. Some evidence of rubbing at bearings, and appearances of  $1/3X$  frequency components in rotor responses were reported from the field [8].

The observed phenomena are related to lubricant starvation at the fluid-film bearing, which results in the journal rubbing against the bearing surface. This rub, consisting of a physical contact of the rotating journal with a stationary bearing surface, has a dry-wet characteristic with highly transient conditions. The original forward-oriented, fluid-related tangential force, which normally drives the fluid whirl [1] became replaced by an unsteady, friction-related tangential force with variable magnitude and orientation. In addition, the non-homogeneous mixture of oil and air provides a lower radial stiffness, which in turn creates a lower natural frequency of the system. This results in the chaotic rotor behavior changing to the locked subsynchronous normal/tight rub mechanism described in Reference [2]. Typically, this subsynchronous behavior is manifested in vibration frequencies of  $1/2X$ ,  $1/3X$ ,  $1/4X$  and  $1/5X$ , depending upon machine rotative speed and the modified natural frequency, due to the rub condition.

When at higher speeds, the rotor is in  $0.47X$  fluid whirl conditions, the journal acts like a pump, pumping the oil out of the bearing, not only through the usual drain openings, but even back through the supply pipes. This pumping action gradually accelerates lubricant starvation. This occurs when the supply pressure of the lubricant is low. The reverse flow of oil and air bubbles was observed in plastic, transparent supply pipes.

Due to ever-changing rubbing surface conditions, the rotor response contains a significant amount of chaotic patterns of vibration [4,5]. There also exist, however, stable patterns, typical rub-related fractional vibrations with frequencies proportional to the rotative speed. In these cases, the unbalance is the driving force of the rub. Two main fractional components exist as stable patterns in different ranges of the rotative speed. They are a  $1/5X$  reverse component with a larger  $2/5X$  forward component and a  $1/3X$  forward component. It is interesting that the  $1/5X$  &  $2/5X$  vibration usually occurs as a transition pattern to a "more stable"  $1/3X$  pattern. The  $1/5X$  vibrational component in the rotor

response exhibits a small circular reverse orbit, accompanied by a larger  $2/5X$  forward, slightly elliptical, orbit, so that the overall orbiting is forward. Exclusive overall backward orbiting is most characteristic of a full annular rub driven by dry friction [9]. Larger unbalance produces more pronounced rub-related vibrations[7].

There is no doubt that the existence of the stable  $0.47X$  fluid whirl in the lower ranges of rotative speeds is affected at higher speeds by the rubbing conditions. The  $0.47X$  fluid whirl becomes unstable in the presence of rub, and disappears, as the fluid circumferential pattern of the flow at the bearing is broken.

All phenomena occurred when the journal was initially centered inside the bearing. The appearance and strength of the observed phenomena significantly decrease when the journal is forced to rotate at a higher eccentricity, due to an externally applied radial force, such as gravity. In this case, the fluid circumferential flow pattern is weaker [1].■

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## Full spectrum cascade plots

**T**he full spectrum is based on the rotor vibrational data from two XY transducers. The Fourier transformation splits the original waveforms into frequency components. Each mono-frequency component represents an elliptical orbit (in particular, it can be a circle or a straight line). From classical mathematics, it is known that an ellipse can be described as a locus of the vectorial sum of two vectors counter-rotating at a constant frequency. An elliptical orbit is, therefore, a sum of two circular orbits, one rotating forward, one rotating in reverse. In the right half plane, the full spectrum plot presents the amplitudes of the forward rotating orbits of all frequency elliptical com-

ponents. In the left half-plane, the full spectrum plot presents the amplitudes of the reverse rotating orbits.

If the orbit of a particular frequency component is circular, it will appear on the spectrum, either in the right plane (if the orbit is forward) or in the left plane (if it is reverse). Elliptical orbits will always result in frequency components in both sides of the plane. Their relative magnitudes, however, immediately indicate the orbital motion direction. If the right-side component is larger, the elliptical orbit is forward. If the left-side component is larger, the orbit is reverse. If they are the same, the orbit is a straight line.■